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VPS: Volumetric Positioning System

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Abstract
In this paper we present the Volumetric Positioning System (VPS), a novel volumetric encoder which is capable of measuring 6D poses of the tool center point (TCP) in a volume of up to 1 m³ with a sampling rate of 10 kHz. Hence, in kinematics like milling machines, robots or parallel kinematics, the VPS provides a direct measurement of the position and orientation of the tool center point with respect to a reference frame. The high measuring rate allows for the integration of the VPS into the control loop of the kinematics, which has already been successfully demonstrated in a parallel kinematics robot [1]. Based on the VPS, a calibration tool for five-axis milling machines has been developed. In first tests, volumetric machine tool calibration and the monitoring of the machine's dynamic characteristics for cross talk compensation have been successfully demonstrated with a position uncertainty of ± 5 µm (95%). System performance in terms of repeatability, accuracy and calibrated machine volume along with the achieved resolution for dynamic machine measurements is presented.

Sensor, Calibration, Metrology, Machine tool

1. The VPS measuring system

For the characterization and calibration of milling machines, robots and parallel kinematics the direct measurement of the position and orientation of the tool center point (TCP) in a volume of about 1 m³ is required. Ideally, this measurement provides a high sampling rate which is sufficient to characterize the dynamic behaviour of the kinematics, which ultimately would allow to incorporate the 6D measurement into the control loop of the kinematics. However, measurement systems providing both high accuracy and high sampling rate in a volumentric measurement are rare. Lasertrackers are a well established technology and provide 3D position with high accuracy and a sampling rate of a few kHz [2, 3]. However, 6D measurements require multiple trackers or an included camera system for photogrammetry [4]. They are often difficult to incorporate into the machine due to the required volume and possible beam blocking during operation. Camera based techniques like photogrammetry are able to cover several targets and achieve 6D pose measurement, but with lower accuracy of about 150 µm and significantly lower sampling rates [5]. Typically, high-resolution is achieved at low sampling rates and vice versa. Recent photogrammetric approaches show an improved accuracy of 50 µm, but come at the cost of a large setup and a low sampling rate of a few Hz [6]. In this paper, we present a volumetric encoder, the VPS, which consists of sensors and targets shown in fig. 1 and which performs 6D measurements with a sampling rate of 10 kHz in a volume of up to 1 m³. The VPS sensor head performs an incremental 2D angular measurement towards the active VPS target with an uncertainty of ± 5 µrad. The acceptance angle of the VPS sensor head is ± 50°. The sensor heads are calibrated at HEIDENHAIN for a distance between head and target of 0.24 m to 1 m. The minimum working distance is 0.2 m. For the VPS targets, no calibration is required. Using a rigid setup of several VPS sensors and targets, a full 6D measurement between the tool center point (TCP) and the reference frame (REF) is achieved. Both position and angular orientation of the TCP with respect to the reference frame are determined which we will refer to as the 6D pose. To determine the full TCP pose, the VPS setup must be designed to provide a minimum of 6 suitable VPS measurements at every measured machine position. Thus, there must be a direct line of sight between the sensor head and at least 3 targets.

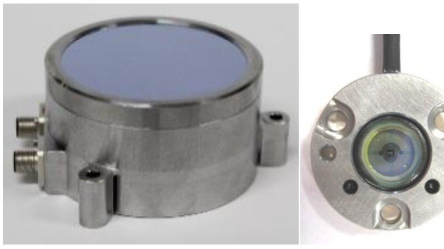


Figure 1. VPS sensor head and VPS target.

A specific VPS configuration, developed for the calibration of five-axis milling machines, is shown in fig. 2. In this configuration, one VPS sensor is attached to the HSK interface of the machine tool (TCP) and the VPS target plate, comprising 24 VPS targets, is mounted onto the working table (REF). Due to the rigid geometrical setup of VPS targets on the target plate, the full 6D pose of the HSK with respect to the working table can be computed if more than 3 targets are detected by the sensor head**.** The green lines in fig. 2 indicate active VPS targets. Typically, the number of active VPS targets is much larger than 3 which increases both accuracy and robustness of the system and allows for system recalibration.

2. Spatial resolution and accuracy

In general, the resolution of the 6D pose computed from the angular VPS measurements depends on the geometry of the VPS setup, the size of the calibrated machine volume and the kinematics of the machine since these factors determine the VPS signals available at every machine position. Thus, the achievable uncertainty of the TCP needs to be analyzed upfront via a sensitivity analysis during the optimization of the VPS setup. In order to achieve accuracy for the measured position, a calibrated sensor head and a calibrated target plate is required. Hence, the VPS sensor head is calibrated at a reference measuring machine at HEIDENHAIN. Further, an Invar artefact is integrated into the VPS target plate which carries 4 of the 24 VPS targets, see fig. 2.

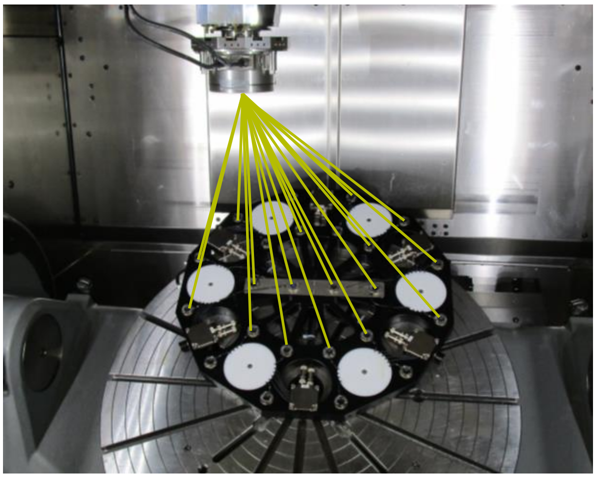


Figure 2. VPS setup for the calibration of a five-axis milling machine. Active targets are visualized with green lines. The Invar artefact is seen in the middle of the VPS target plate

The distances between the 4 VPS targets on the Invar artefact are calibrated at HEIDENHAIN and hence fix the scaling factor of the computed machine poses for varying thermal conditions. In the error budget of the standard uncertainty of the VPS measurement [**7**], random errors can be neglected due to the significant noise reduction via averaging over 100 - 1000 samples per standstill pose which typically gives resulting noise in the range of 30 - 100 nm. In principle, the standard uncertainty is dominated by thermal drift, humidity and vibration and hence these systematic errors have been addressed in the VPS design. Due to the internal design of the VPS sensor head, the thermal drift could be minimized to < 0.2 µrad/K with no significant influence of humidity in the range of 30% to 93% rH.

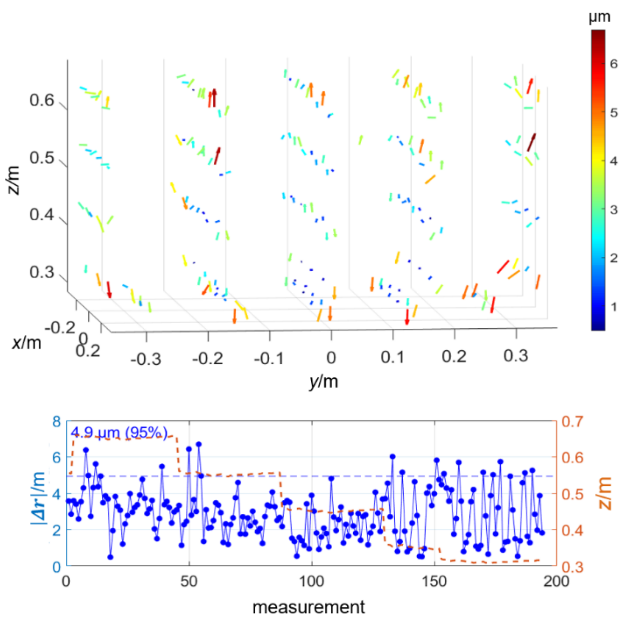


Figure 3. Position error determined at a reference measuring machine at HEIDENHAIN. A volumetric position uncertainty of ± 5 µm (95%) is achieved.

Further, the sensor head features a stiff mechanical design with the lowest eigenfrequency at 2 kHz. With moving LEDs, highly dynamic applications have been tested for speeds up to 5 m/s and accelerations of 150 m/s² [1]. No significant influence on accuracy and reproducibility has been observed. Accuracy tests were performed at a reference measuring machine at HEIDENHAIN and the results are shown in fig. 3. During the calibration, for each measured standstill position, 1000 samples were collected for each of the 32 VPS targets giving a total measurement time of 3.2 s. The calculated position is compared to the reference position and the volumetric accuray is determined, i.e. the magnitude of the 3D position error. For a volume of 700 x 700 x 300 mm³, a volumetric position uncertainty of ± 5 µm (95%) is achieved with a calibrated VPS sensor head in a well controlled environment. The upper plot of fig. 3 shows the error vectors of the VPS measurements, the lower plot the respective magnitudes. Note, that the center range shows a higher accuracy than the the outer edges of the measured volume. The position uncertainty of ± 5 µm (95 %) can be transferred to the shop floor. It has been reproduced on a milling machine using seven traceable fiberguided absolute interferometers, see fig. 4.

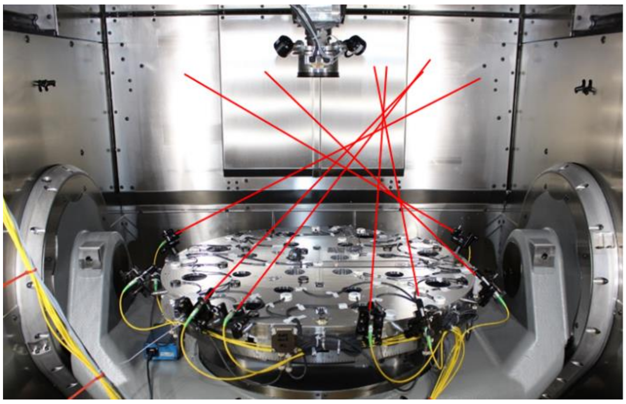


Figure 4. Reference setup with seven interferometers for accuracy validation of the VPS position measurement in the milling machine. The skew interferometric measuring lines are roughly added for illustration. In the photo, VPS sensor and targets are protected by covers.

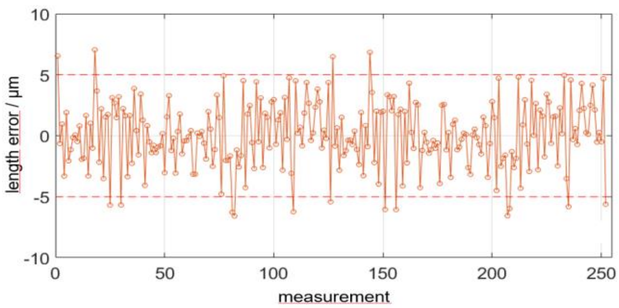
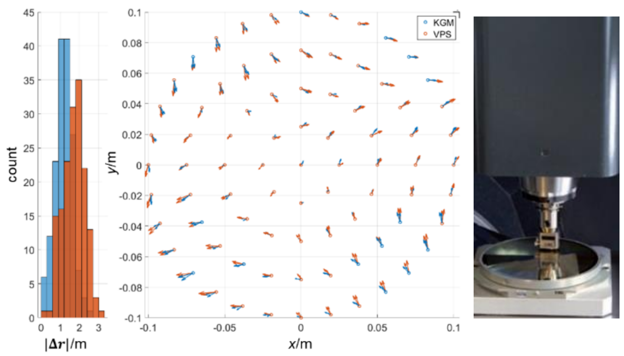


Figure 5. The VPS distance measurements correspond to the respective length measurements of the traceable fiberguided interferometer within an uncertainty of ± 5 µm (95%) on the tested measuring lines.

The retroreflectors of the interferometers are mounted to the spindle interface along with the VPS sensor head. Seven interferometer heads are attached to the VPS plate which is mounted onto the working table of the milling machine and carries 32 VPS targets. The interferometer heads are aligned in different directions to achieve a skew pattern of measuring lines through the traversing range of the milling machine (indicated in red).This skew line pattern is used to confirm the volumetric accuracy of the VPS with linear measurements. Simultaneous standstill measurements of interferometer and VPS are performed at 10 positions on each measurement line for both directions of machine motion. The VPS measurement averages over 500 samples per target and the resulting distances between the adjacent positions were calculated for both interferometer and VPS. The complete procedure is repeated once and a total of 252 distances are compared. The result is shown in fig. 5 and confirms the ± 5 µm (95%) position uncertainty of the VPS in the environment of a milling machine. The VPS has also been compared to the KGM 282, a 2D reference encoder with an accuracy grade of ± 1 µm [8], see fig. 6. Since the KGM is a planar measurement system, KGM and VPS positions are compared in the *xy*-plane at z = 266 mm above the working table. At this location, the *xy*-resolution of the VPS is below 1 µm and the deviation from the KGM measurements is < 1 µm (95%).



a) b)

Figure 6. a) Comparison of KGM 282 and VPS measurements in the horizontal plane at a height of z = 266 mm above the working table. b) HEIDENHAIN KGM 282.

3. Calibration of five-axis milling machines

For the calibration of five-axis machine tools, an automated procedure has been developed. Currently, kinematics with linear axes at the spindle and rotary axes at the working table are supported. All results presented in this section were measured on a 5 axis milling machine featuring a kinematic chain with linear axes *Y*, *X* and *Z* at the spindle, and rotary axes *A* and *C* at the working table, compare fig. 2 and fig. 4. We focus on the calibration of the three linear axes, the result is a KinematicsComp table of 6D corrections [9] computed for the positions of the *X*, *Y* and *Z* axis. The rotary axes can be characterized by separate 6D measurements once the linear axes of the machine are calibrated. Typically, a 7 x 7 x 9 grid of *xyz* machine positions spanning a maximum traversing range of 800 x 800 x 600 mm³ is the base of the calibration. As evident in fig. 2, the VPS target plate is mounted onto the working table with a lateral displacement to the *A* axis. In combination with *A* axis angles of ± 30°, this displacement extends the calibrated machine volume significantly in the vertical direction since both higher and lower positions of VPS targets are achieved. This procedure allows to cover the lower vertical traversing range of 5 axis milling machine, which might extend close to or even below the working table. Besides the vertical extension, also a lateral extension of the calibrated machine volume is achieved via additional measurements at C = 0°, 90°, 180°, 270° for a horizontal working table at A = 0°.

At each machine position of the calibration, 100 samples are recorded and averaged for each VPS target which is in measuring range. On all positions, the angular VPS measurements must provide sufficient information for 6D pose computation and also comply to the current minimum VPS measuring distance of 240 mm to the VPS targets. This is guaranteed by automatic trajectory planning in the VPS software.

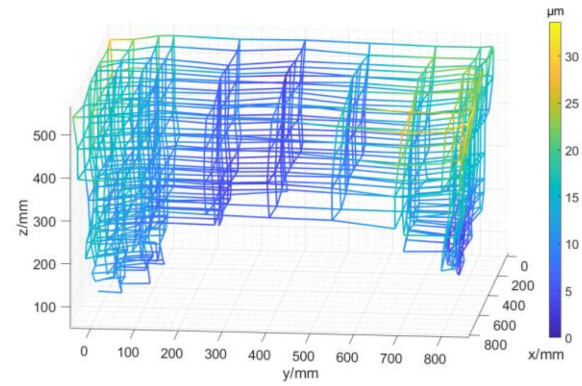


Figure 7. VPS calibration measurement of a five-axis milling machine. Deviations of the measured from the nominal machine positions are enlarged 2000x and encoded in color. The respective machine is shown in fig. 2 and fig. 4.

The machine positions measured at different table orientations are stitched into one common VPS calibration measurement. A typical result is show in fig. 7. Note the significant extension of the VPS calibration measurement in *z* towards the working table at outer *y* positions, where the distance from the VPS targets to the VPS sensor head is enlarged via rotation of the *A* axis. Based on the VPS calibration measurement, a calibration table is computed for the complete *xyz* range of the machine. For the computation of the machine's calibration table in the gap of the VPS calibration measurements at lower positions of the *Z* axis, a rigid body model is assumed for the *Z* axis. This is a valid assumption since the *Z* axis is the last axis in the *Y-X-Z* kinematic chain of the milling machine to the spindle and its position error is hence assumed to be independed of the position of the other machine axes. For the *X* and *Y* axis however, deviations from a rigid body model can be identified and accounted for due to the rich volumetric data gathered during the VPS measurement. A typical calibration table as determined by the VPS measurement for the complete traversing range of the milling machine is shown in fig. 8. The cube shows the 2000x enlarged deviation from the ideal rectangular *xyz* cube of the machine tool shown in fig. 2 and fig. 4, the color encodes the magnitude of the deviation. For error correction, the respective KinematicsComp table can be uploaded to the HEIDENHAIN TNC, the numerical control of the milling machine, via the VPS software. Typically the machine calibration takes around 45 min and consists of 800 – 900 machine positions in total. Currently, *AC* and *BC* kinematics at the working table are supported.

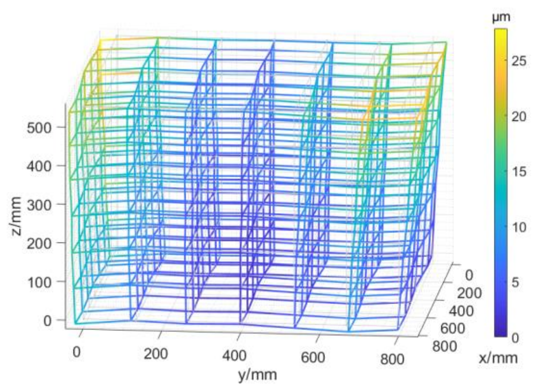


Figure 8. The calibration table determined by the VPS for the traversing range of the milling machine. Deviations from the nominal positions are enlarged 2000x and encoded in color. The respective machine is shown in fig. 2 and fig. 4.

5. VPS realtime measurements

After setup and initialization of the VPS, the continuous 10 kHz measurement of the 6D machine pose is possible with the realtime data provided via a UDP link. The high sampling rate allows to integrate the VPS as an volumetric encoder into the control loop of the kinematics, which has already been successfully demonstrated in a parallel kinematics robot [1]. In the context of milling machines, the VPS realtime measurement allows to characterize dynamic position deviations of the milling machine on user-defined trajectories. An example is shown in fig. 9 where the pose of the working table with respect to the HSK interface is shown for repeated ± 100 mm movements of the *Y* axis. The initial speed is 2 000 mm/min, the speed is increased by 2 000 mm/min after every cycle giving a maximum speed of 20 000 mm/min.

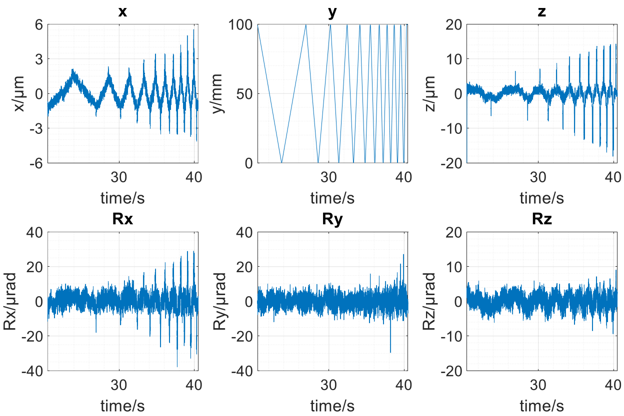


Figure 9. VPS realtime measurement of a repeated *y* ± 100 mm machine movement with a speed of 2 000 mm/min to 20 000 mm/min. The machine speed is increased by 2 000 mm/min after every *y* cycle. The VPS measurement of the working table with respect to HSK interface has a sampling rate of 10 kHz, the bandwidth is set to ca. 400 Hz.

The realtime measurement of the 6D machine pose reveals a highly dynamic, parasitic motion of the *Z* axis of up to ± 15 µm accompanied by similar motions of the *X* axis of ± 5 µm and rotations around the *X* axis of up to *Rx* ± 40 µrad. These dynamic features are induced by acceleration in the reversal points and are superposed by systematic movements of ± 2 µm revealed both for the *X* and *Z* axis. Note that the directions of all parasitic motions depend on the direction of *y* movement. As evident in fig. 10a, the machine's parasitic motions are monitored by the VPS with high spatial and temporal resolution. Fig. 10b shows the measurement repeated with active TNC Cross Talk Compensation (CTC), where the dynamic *z* motion of the machine is corrected in the numerical control

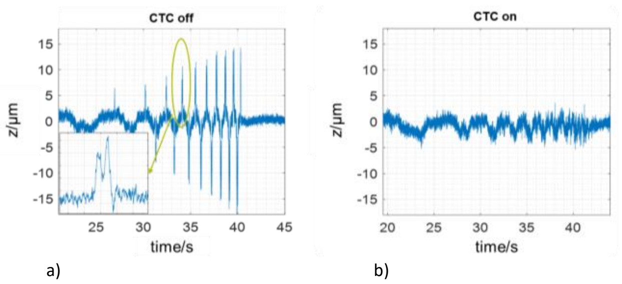


Figure 10. Comparison of the vertical machine motion with and without the TNC Cross Talk Compensation (CTC). The CTC compensates the machine's dynamic parasitic motions in *z*.

6. Summary and outlook

The VPS, a volumetric encoder system, has been presented along with its application for the calibration and the dynamic characterization of five-axis machine tools. The high sampling rate and accuracy allows for numerous applications in a volume of up to 1 m³.

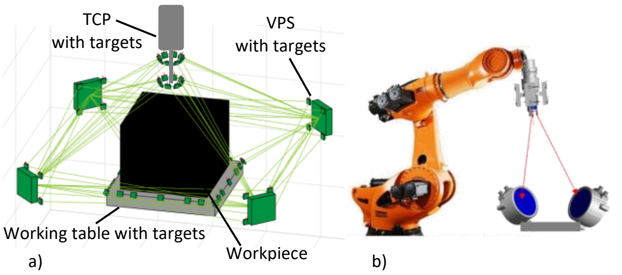


Figure 11. a) VPS metrology frame for machine pose measurement. **b)** VPS as a high accuracy robot guiding system.

As an example, fig. 11a shows a concept for the machine pose measurement with a multitude of targets both at the TCP interface and at the working table via a network of VPS measurements completely circumventing a large working piece on the working table. Due to additional targets on all VPS sensor heads, a continuous detection of the TCP pose and the pose of all four VPS sensors is achieved simultaneously with respect to the working table. Thus, drifts of the position or the orientation of the four VPS sensors are compensated for and hence have no influence on the measured TCP pose. Fig. 11b shows a robot guiding system comprising two VPS sensor heads at the reference frame and a multitude of VPS targets at the robot endeffector. With this setup, a wide range of robot poses are covered if LEDs are mounted on all outer faces of the endeffector. In both cases the accuracy at the TCP depends on the implemented system configuration. These examples give a good impression of future applications of the VPS.

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